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Thermodynamic approach for designing the two-phase motive nozzle of the ejector for transcritical CO2 heat pump system

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Abstract

In this paper, a one-dimensional thermodynamic analysis is developed to design and evaluate the performance of primary nozzles in two-phase ejector utilized in the transcritical CO_2 heat pump system. Two thermodynamic approaches (ideal and non-ideal) are adapted to model the expansion processes for comparison. The operating parameters and correlations were adapted from verified experimental and theoretical studies in open literatures. Mass flow rate, density and quality of the working fluid (CO_2) across the primary nozzle are calculated. The isentropic expansion of CO_2 through the coverage-diverge (C-D) nozzle is then studied. The supersonic properties of the refrigerant such as Mach number, velocity and the speed of sound are obtained and the relations between them are analysed. Other design parameters related to the nozzle geometrical domain namely the area, the area ratio and the diameters are deduced. The results show that at the nozzle exit section, two phase flow and normal shock wave were detected. There is a similar trend between ideal and non-ideal models in terms of supersonic flow characteristics. The domain, boundary conditions and results of non-ideal model could be further verified by a CFD software in 2D and/or 3D models.

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Keywords: *Primary nozzle design; two phase ejector; CO2 heat pump system;Heat pump system;*

1. Introduction

Using two-phase ejector as an expansion device is one of the most promising solution for tackling the high irreversibility during the expansion process in transcritical CO_2 Heat Pumps (HPs) [1, 2]. HP systems utilizing a two-phase ejector have been demonstrated both theoretically and experimentally, showing significant improvement of

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coefficient of performance (COP). Essentially, this is achieved by reducing the compressor work, increasing the evaporator cooling capacity, and decreasing the evaporator size [2, 4, 7-10]. In theory, the main function of an ejector is to convert the potential energy contained in the high-pressure refrigerant flow into kinetic energy through an isentropic process [3].

As shown in Figure 1, an ejector normally consists of a primary nozzle, a suction nozzle, a mixing section, a constant area section and a diffuser section [4]. The main function of the primary (motive) nozzle is to expand the refrigerant exiting the gas cooler from subsonic speed to supersonic flow. Simultaneously, it reduces the pressure to be less than the evaporator pressure in the mixing chamber, entraining the refrigerant vapor from the evaporator into mixing zone.

A recent study by Ahmed *et al.* has conducted a thermodynamic mathematical model for ejector design [5]. They also had extended their simulation to calculate the diameters of the throat and exit of the primary nozzle. However, other design parameters such as the area and the contour of the nozzle were not calculated. In addition, the results have not shown the supersonic characteristics of the CO_2 flow such as Mach number and speed of sound.

In our study, these design parameters as well as the refrigerant supersonic characteristics have been evaluated to design the motive nozzle of the two-phase ejector. For comparison purposes, two approaches have been adapted to calculate the thermophysical properties of the CO_2. In the Ideal model (I-Model), the properties are evaluated based on ideal gas law, whereas in the Non-Ideal model (NI-Model) the thermophysical properties are calculated by REFPROP software. Both models are coded by MATLAB software.

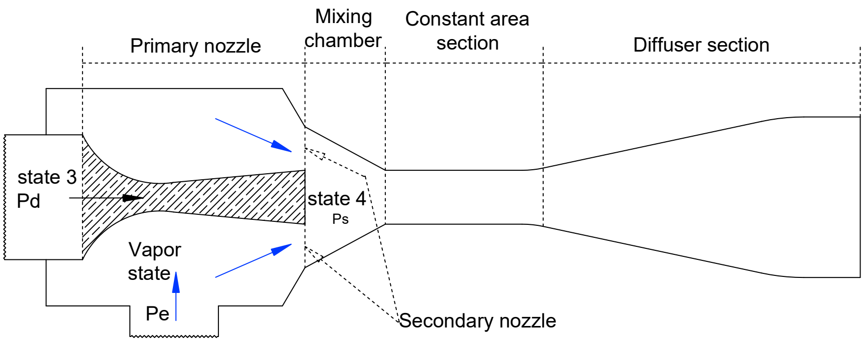

Figure1 the Tow-phase ejector configuration.

2. Mathematical models

The following working conditions and assumptions have been made in the current study.

- CO_2 enters the primary nozzle as a supercritical steady adiabatic quasi one-dimensional flow with pressure of 11 Mpa and temperature of 35°C.
- An isentropic flow is assumed for the I-Model; while for the NI-Model, the entropy is calculated by REFPROP and nozzle isentropic efficiency obtained from the literature.
- A constant mixing pressure approach ($P_s = (P_e - 30)$ kpa) is adapted in the mixing camber to satisfy the chocking condition [6].
- A stagnation condition is assumed at the inlet of the motive nozzle ($U_3 = 0$).
- The isentropic efficiency of the motive nozzle is assumed 85% [5].

The energy equation for the steady adiabatic quasi one-dimensional flow is:

$$\frac{U_3^2}{2} + h_3 = \frac{U_4^2}{2} + h_4 \tag{1}$$

State 3 represents the refrigerant states at both nozzle inlet and gas cooler exit. Whereas state 4 represents the state at both the nozzle exit and the mixing chamber as shown in Figure 1. The total enthalpy changes across the nozzle

$(h_4 - h_3)$ is divided into number of segments (N) to obtain the enthalpy change at each segment(h_{Nozzle}).

$$h_{Nozzle} = \frac{(h_4 - h_3)}{N} \tag{2}$$

The same principle is applied for pressure, assuming the inlet pressure is the same for the gas cooler pressure (P_d) and the outlet pressure is the same for the mixing chamber (P_s). Other CO_2 thermodynamic properties such as entropy, density and quality is calculated by REFPROP for each segment.

The velocity of the working fluid at the exit of the nozzle is measured from equation (1), with the assumption of a stagnation condition. The nozzle area is the ratio of the CO_2 mass flow rate ($\dot{m}_p$) over the mass flux ($\rho \times U$). Therefore, the diameter is calculated as follow:

$$D_{Nozzle} = 2 \times \sqrt{\frac{\frac{\dot{m}_p}{\rho \times U}}{\pi}} \tag{3}$$

Equations (1-3) were iterated for (N) times to determine their values for each segment.

Some thermophysical properties for the working fluid such as speed of sound, Mach number, dynamic viscosity and specific heat does not exist for two-phase flow in the REFPROP, so the following isentropic equation is used to calculate the speed of sound and Mach number:

$$M = \frac{U}{a} = \frac{U}{\sqrt{\frac{\Delta P}{\Delta \rho}}} \tag{4}$$

Two main equations are used in the design of the supersonic coverage-diverge nozzle; the Area-Velocity relation (i.e., Equation (5)) and the Area-Mach number relation (i.e., Equation (6)) as follow:

$$\frac{\partial A}{\partial U} = (M^2 - 1) \times \frac{A}{U} \tag{5}$$

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{k+1}\left(1 + \frac{k-1}{2}M^2\right)\right]^{\frac{(k+1)}{(k-1)}} \tag{6}$$

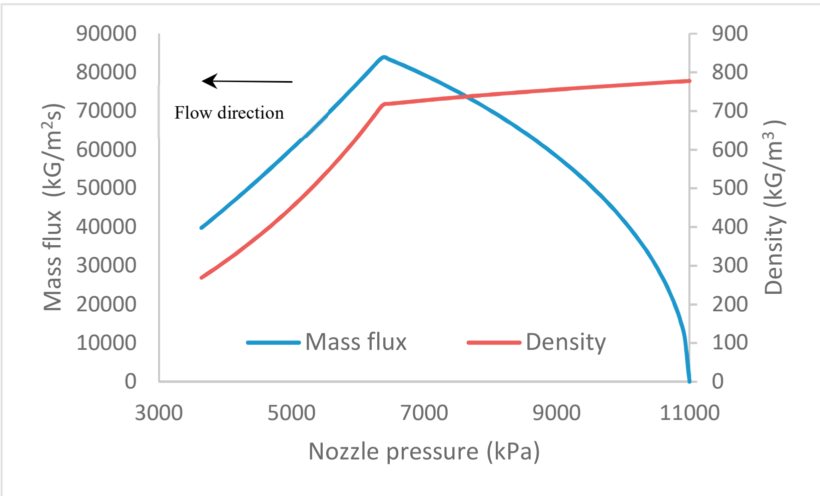

Figure 2. The relation between mass flux and density of the CO_2 with pressure across the primary nozzle.

3. Results

The results for the NI-Model are shown in Figures 2-6. Figure 2 illustrates the changes in density, mass flux and pressure of the working fluid along the primary nozzle. It shows that the pressure decreases from the gas cooler pressure (P_d=11000 kPa) to the mixing chamber pressure (P_s=3643 kPa). The mass flux increases significantly until it reaches a maximum value at the throat section pressure (6541 kPa) then it decreases sharply. The mean isentropic changes in CO_2 density ($\Delta\rho$) between the inlet and the throat section is relatively small which indicates that this part is a coverage section and the flow is incompressible. Thereafter, from the throat section up to the nozzle exit, the density decreases, showing that the flow become compressible in a diverge nozzle counter. The tips of both curves identify the throat section of the nozzle.

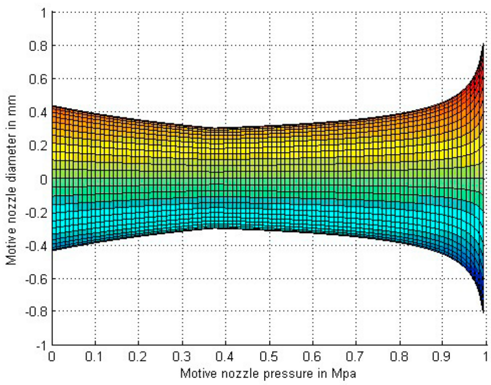

Figure 3. 2D geometrical domain of the primary nozzle with pressure.

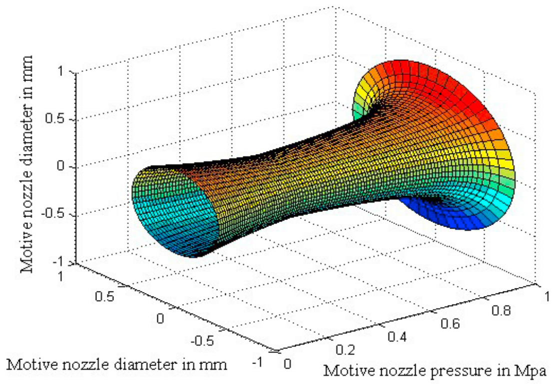

Figure 4. 3D geometrical domain of the primary nozzle with pressure.

Figures 3 and 4 show the 2-D and 3-D geometrical domain of the primary nozzle for the NI-Model. The figures support that the motive nozzle is a coverage-diverge nozzle. At the throat pressure, the diameter of the nozzle reaches its minimum value (0.603 mm) which represent the throat diameter.

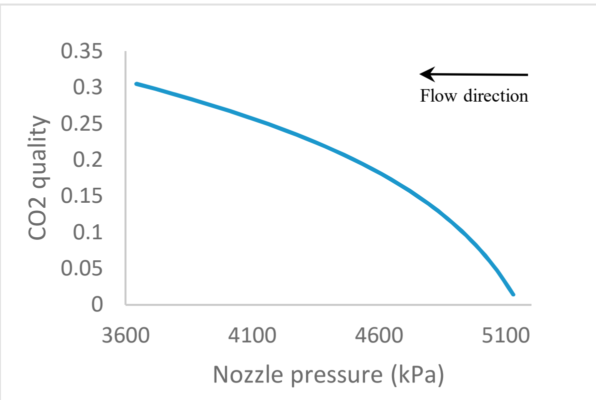

Figure 5. The correlation between CO_2 quality and pressure.

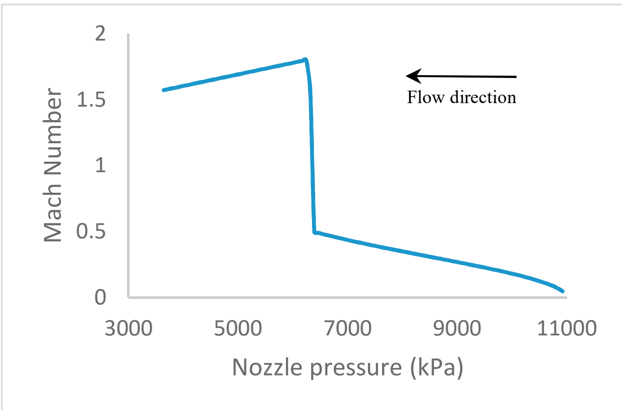

Figure 6. The correlation between Mach number and pressure.

Figure 5 shows the changes of quality of the working fluid along the nozzle when the flow transformed from a supercritical into a two-phase state. After passing the throat section and at a specific pressure (5129 kPa), the working fluid starts to change into a two-phase flow and exits the nozzle with a quality of nearly 30%. As shown in Figure 6, the working fluid expands across the primary nozzle from subsonic to supersonic speed. It enters the nozzle at a stagnation condition (U=0), then it accelerates across the coverage part into a subsonic velocity (Mach <1). At the throat section, the velocity increases into sonic speed (Mach=1), indicating that the chocking condition is satisfied. The refrigerant flow expands supersonically within the diverge section (Mach >1), where it encountered a normal shock wave leading to a reduction in Mach number from nearly (1.68) to (1.572) at the exit of the nozzle. A comparison between I-Model and NI-Model has been conducted and represented in Figures 7-12. In Figures 7 and 8, both CO_2 velocity and speed of sound are presented against Mach number. In I-Model, both velocities are equal when Mach number is 1. Whereas in NI-model, they are equal at a Mach of approximately 1.3. Figures 9 and 10 describe the Area-Velocity relation (equation 5) for both models. The Figures show that when M<1, the values of the derivative are negative$\left(\frac{dA}{dU} < 0\right)$. Whereas when M=1, the ratio of $\frac{dA}{dU}$=0 for both simulations. The derivative ratios for both models are positive $\left(\frac{dA}{dU} > 0\right)$ when M >1.

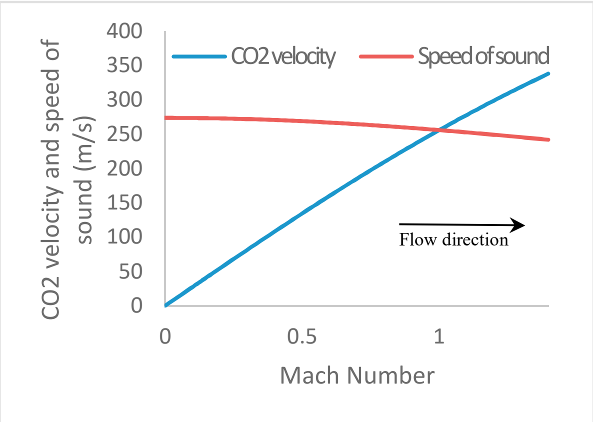

Figure 7. Relation between CO2 velocity and speed of sound with Mach number for I-model.

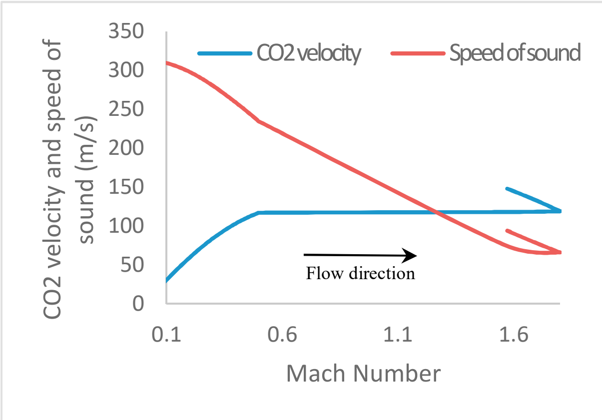

Figure 8. Relation between CO2 velocity and speed of sound with Mach number for NI-model.

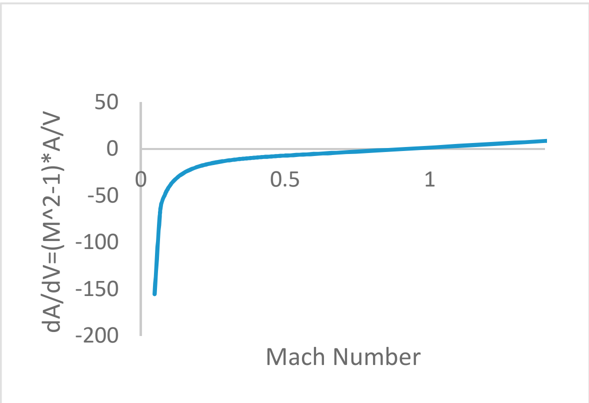

Figure 9. Area derivative over velocity derivative with Mach number for I-Model.

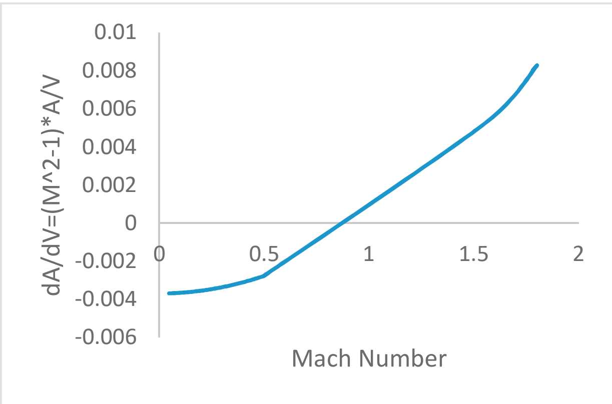

Figure 10. Area derivative over velocity derivative with Mach number for NI-Model.

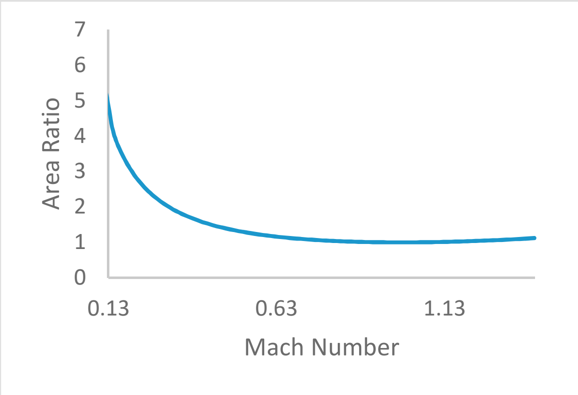

Figure 11 the Area-Mach number relation for I-model.

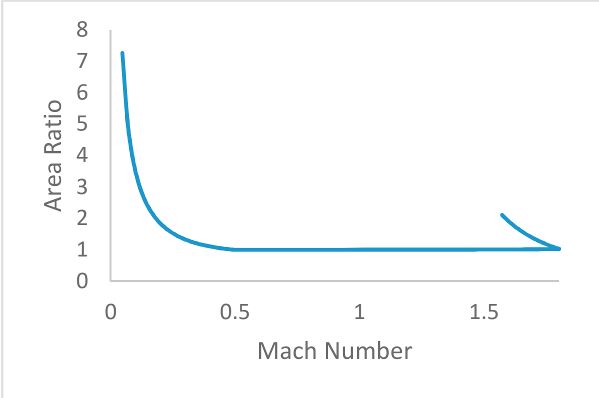

Figure 12 the Area-Mach number relation for NI-model.

Figures 11 and 12 describe the Area-Mach relation (equation 6) for both models. The local Mach number at any point across the nozzle is a function of the ratio of local area to throat area. In I model (figure 11), for M<1, the area ratio indicates the converge section of the nozzle, whereas when M>1, the area ratio implies the diverge path of the nozzle and for M=1, an area ratio of 1 represent the throat section. In the NI-model, it can be noticed that the throat section is relatively longer than the I-Model as shown in Figure 12. For this section, where area ratio is 1, the Mach number range from 0.4 to 1.68. This could indicate that the primary nozzle shape predicted by the NI-model does not follow the typical converge diverge pattern. Instead, it has a converge-straight throat section-diverge configuration.

4. Conclusion

A thermodynamic analysis has been conducted to investigate and design the motive nozzle in the two-phase ejector. Ideal gas law and REFPROP software were used to drive the thermophysical properties of the CO_2 in two different models for comparison purpose. Working conditions and some correlation were adapted from decent studies in the literature. Number of design and performance parameters such as diameter, area, density and mass flux, as well as CO_2 supersonic characteristics were obtained. Results confirm that the contour of the nozzle is a converge diverge nozzle with a relatively long constant area throat section. In addition, a normal shock wave was detected through the expansion process leading to a reduction in the refrigerant velocity. Also, CO_2 leaves the nozzle as a two-phase flow. Although this steady is 1D analysis, further validation using a 2D model in a CFD software is recommended.

Nomenclatures		**Nomenclatures**		**Subscripts**	
A	area, m^2	M	Mach number	s	mixing chamber
a	speed of sound, ms^{-1}	$\dot{m}_p$	mass flow rate, kg/s	e	evaporator
COP	coefficient of performance	P	pressure, kPa	p	primary nozzle
D	diameter, m^2	S	entropy, kJ/kg.k	d	gas cooler pressure
G	mass flux, kg/m^2s	U	velocity, m/s		
h	enthalpy, kJ/kg	ρ	density, kg/m^3		

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